

FURTHER INVESTIGATIONS OF DIFFUSER

AUGMENTED WIND TURBINES*

PART I - EXECUTIVE SUMMARY

by

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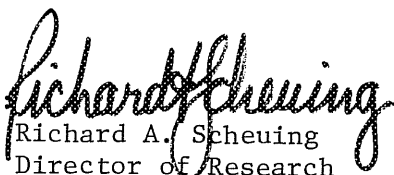

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ABSTRACT

The Diffuser Augmented Wind Turbine (DAWT) is one of the advanced concepts being developed to improve the attractiveness of wind energy as an energy resource alternative. This work is dedicated to reduce the specific cost of available power by minimizing the capital cost of energy conversion machinery.

Diffusers can increase turbine power output primarily by increasing mass flow rate through the blades. This is because of controlled diffusion of the turbine wake, which lowers the exit plane pressure considerably below atmospheric. The diffuser duct surrounding the turbine also tends to reduce turbine blade tip losses.

This project used a multiphased experimental approach involving three wind tunnel test facilities, and models of several compact diffuser configurations. Screens to simulate a wind turbine, and a three-bladed, fixed-pitch turbine have been used with the diffuser models. A candidate baseline design is described, and some of the key technical and economic issues which can lead to future full scale implementation are discussed.

EXECUTIVE SUMMARY

INTRODUCTION

The Advanced and Innovative Concepts Project of the U.S. Department of Energy's Wind Energy Program is dedicated to improve the attractiveness of wind energy conversion systems (WECS) as an energy alternative, by reducing the specific cost of available wind power by minimizing the capital cost of energy conversion machinery. The DAWT is one of these advanced concepts currently under development.

The DAWT concept takes advantage of the greatly reduced (subatmospheric) pressure created behind the turbine by the diffuser, which causes more mass to flow through the DAWT than an unducted rotor. Because wind power is the product of flow rate and turbine pressure drop, the resulting output of a given diameter turbine in a given wind velocity is increased significantly.

Our departure from traditional diffuser technology was to recognize that economic factors of power production necessitate development of very short and compact diffusers. Thus, sacrifice of technical perfection is justified if the energy conversion system can produce low cost power.

TEST RESULTS

Several compact diffuser configurations have been evaluated in a multi-phased investigation using three test facilities and about 150 test models of different sizes and geometry. In our tests we have used screens to simulate a wind turbine, as well as a three-bladed, fixed-pitch turbine rotor assembly.

The most promising compact diffuser approach emerging from this project work employs slot-injected external air to energize the boundary layer of the internal, or core flow. Figure 1 schematically indicates how the high energy air prevents core flow separation in the rapidly diverging boundary layer controlled (BLC) diffuser. The candidate baseline diffuser design features an included angle of 60 degrees, a length-to-inlet diameter ratio of 0.5, and a 2.78 area ratio. The inlet slot sizing provides an initial boundary layer control airflow area that is 20 percent of the core flow area. A secondary slot located downstream provides additional tangential airflow, equal to 8 percent relative to the core flow, to further re-energize the boundary layer.

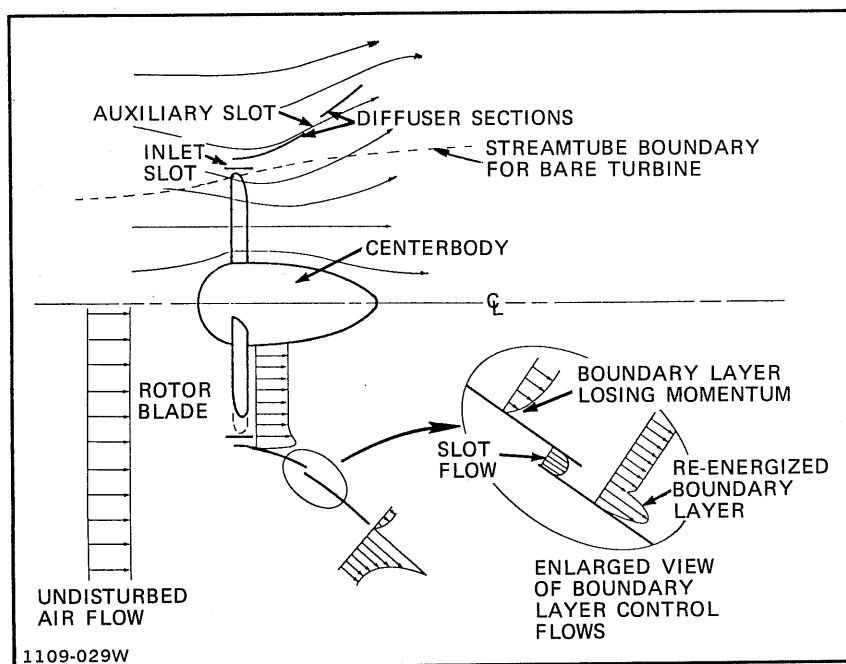


Fig. 1 Schematic Representation of Flow Field for the Baseline DAWT Diffuser Design

Major conclusions derived from the test program with the baseline diffuser models are:

- For the same turbine speed ratio, the baseline diffuser produces about four times the power of a bare turbine, and about three times the power of a short cylindrical ducted turbine
- For the same disk loading (i.e., $C_T \approx 0.4$), the turbine-equipped DAWT gives two times the power coefficient of a screen-equipped diffuser of the baseline design
- The swirl of the turbine wake produces a more efficient diffusion process in high-included angle, short diffusers, than is possible with only boundary layer separation suppression measures.

These major points are supported by the test data shown in Figs. 2 and 3. The linear relationship of C_T with q_2/q_0 , obtained from screen data, permits the parabolic shaped \bar{r} vs. C_T curve extrapolation (dotted line of Fig. 3) because $\bar{r} = [C_T(q_2/q_0)^{3/2}]/0.593$. The extrapolation predicts a peak augmentation ratio at a disk loading of about 0.9.

Over the range of conditions tested by the wind tunnel model shown in Fig. 4, the disk loading varies nearly inversely linear with turbine tip speed ratio and the dynamic pressure ratio, q_2/q_0 . Peak augmentation ratio, \bar{r} , obtained with a turbine for the near-unity speed ratio is 3.4 when referenced to the ideal maximum power coefficient of 0.593; the accompanying local disk loading is about 0.42.

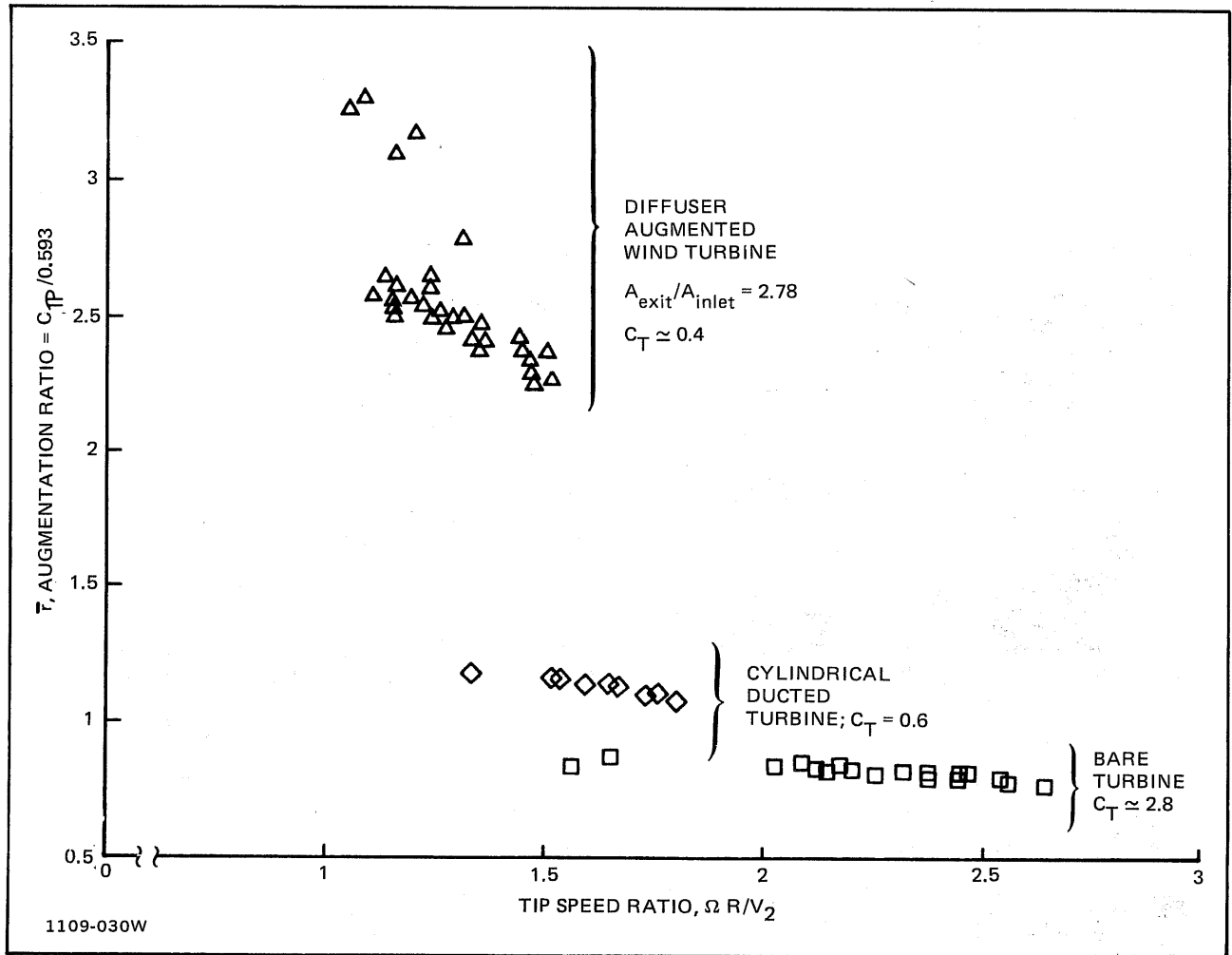


Fig. 2 Comparison of Turbine Performance in the Wind Tunnel for Different Augmentation Systems

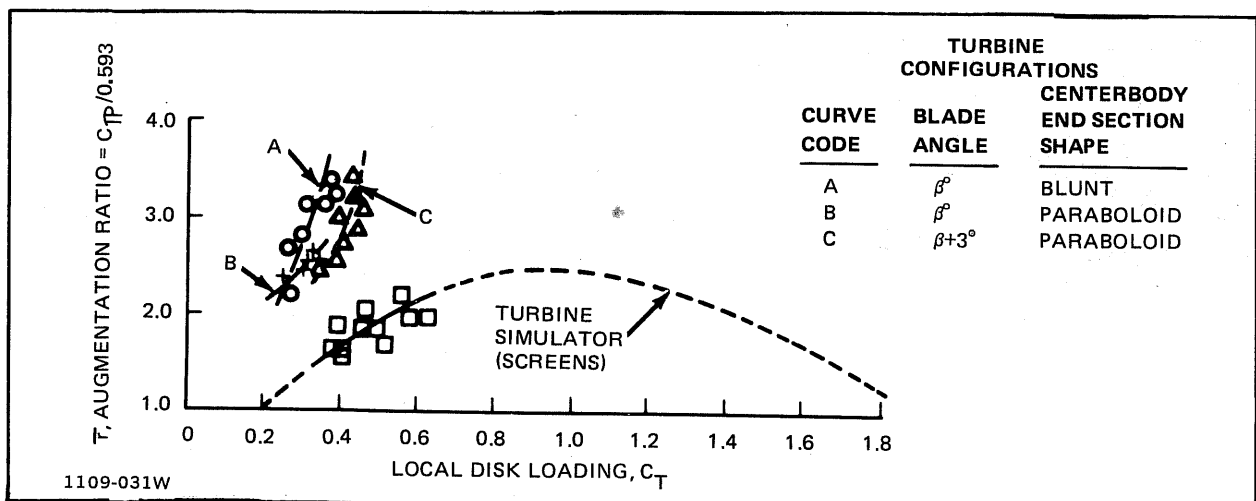


Fig. 3 Comparison of Baseline Diffuser Wind Tunnel Test Data with Turbine and Turbine Simulation by Screens

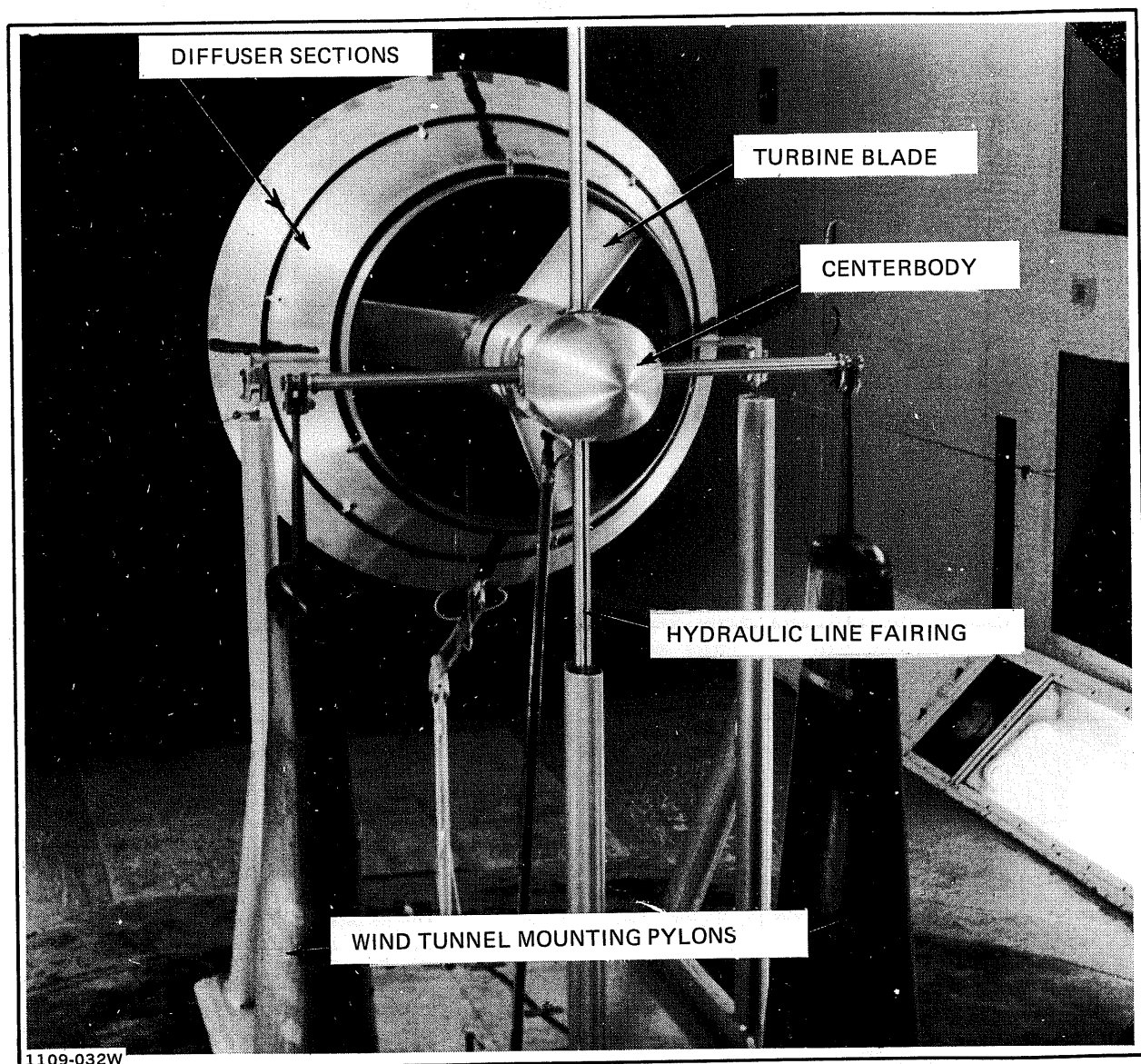


Fig. 4 DAWT Baseline Model Installation in the 2.1 x 3 m Wind Tunnel with Three-Bladed, Constant Chord Wind Turbine and Paraboloid Centerbody End Pieces. Turbine diameter is 18 inches (0.46 m).

With the reasonable assumption that actuator disk theory of conventional WECS is applicable to the DAWT, had we been able to operate in the test facility at a turbine tip speed ratio of 5 or 6, which is more characteristic of modern wind turbine practice, instead of the actual 1.0, there would have been a 37 percent increase in power conversion efficiency. As a result, the augmentation ratio would have been expected to reach about 4.7 at a disk loading of approximately 0.4. If the turbine performance were to have followed the \bar{F} vs C_T trend of the screen-equipped diffusers, then a peak augmentation ratio value of 6.3 would have been expected at $C_T = 0.9$.

Other results obtained from the test programs were:

- A subatmospheric exit plane pressure exists that is essentially invariant with disk loading
- A short constant area section is needed downstream of the turbine to initiate the core flow diffusion process against the adverse pressure gradient
- Power augmentation increases with diffuser exit-to-inlet area ratios up to 3.0. (Further improvements for greater area ratios are theoretically indicated.)
- General agreement with the observed performance data is obtained by a one-dimensional momentum theory model
- The presence of a ground plane within 1/2 a turbine diameter from the exit plane seems to improve augmentation
- A combination of simulated wind profile and ground plane effects produce up to 10 percent improved augmentation, compared to a no ground, uniform flow condition
- Centerbodies with cross-sectional areas up to about 10 percent of the turbine disk area produce negligible effect on augmentation in screen tests
- Small angular changes in pitch or yaw (to about 15 degrees) create negligible variations in overall diffuser core flow and performance.

ENERGY COST FACTORS

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The experimental data and theoretical considerations strongly suggest that the DAWT can provide substantial power augmentation benefits, to factors of about six. An additional and significant feature of DAWT operation is the improvement of plant capacity factor, because the diffuser causes an acceleration of the wind approaching the DAWT turbine. This is in great contrast to the slowing up of the free wind that enters a conventional turbine rotor. The net result is that the DAWT turbine can start to produce useful power at much lower free wind speeds than a conventional wind turbine, and can reach and maintain rated power output over a wider range of speeds. In average wind variance environments of candidate installation sites, the DAWT typically can have up to 150 percent of the annual capacity factor of conventional machines. Therefore, the annual energy output of the DAWT will be approxi-

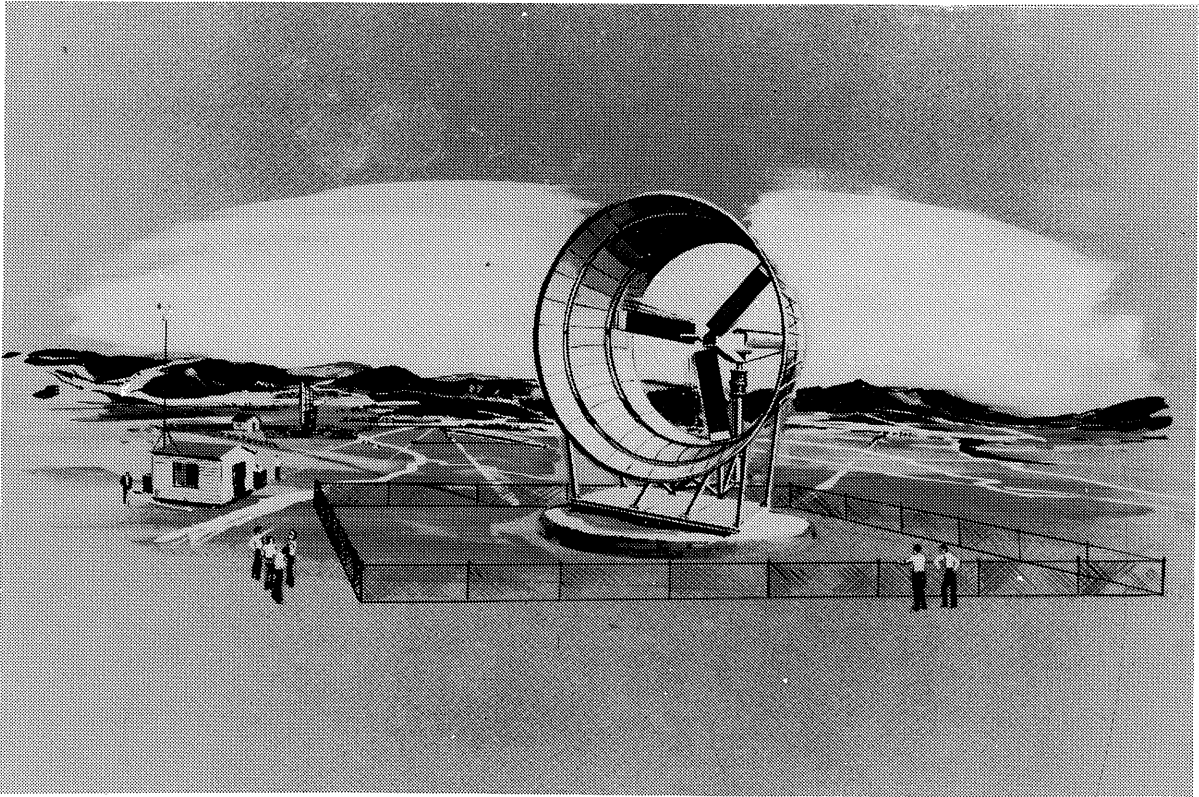
mately $(1.5\bar{r} - 1)$ greater than a conventional WECS of the same rotor diameter, at a given geographic location and free wind speed.

The wind energy field lacks broad modern experience and hard cost data to enable credible capital costs to be generated for large quantity WECS production. Accurate costing of a commercialized diffuser also is affected by several interacting issues which have not as yet been thoroughly examined. These key issues include size and annual delivered energy rating, siting, design approach, and manufacturing approach.

In the face of the present lack of good cost estimates for large diffusers, there still exist reasonable expectations that the incremental cost of the diffuser component will probably be more than offset by the improved productivity of the DAWT. This is based on U.S. Department of Commerce statistics of sales value to material cost (or weight) for typical industries with similar products. The net result should be that the DAWT yields lower busbar cost than conventional wind turbines of equal rotor size and free wind speed.

RECOMMENDATIONS

The economics of power production put a high value on inexpensive capital equipment in preference to marginal engineering refinements. Although rough estimates and projections of DAWT costs appear to indicate competitive prospects relative to current fossil fuel generation performance, the lack of DAWT operational experience clearly makes these paper studies incapable of producing a high degree of confidence. We perceive an urgent need to program the technically advanced system developments beyond the laboratory to a meaningful field test and demonstration system as depicted in Fig. 5. In our opinion, only through such exposure to the long term natural environment, where physical visibility and documented power production of meaningful scale DAWT equipment can provide irrefragable evidence, will the needed credibility be generated to promote widespread market acceptance and commercialization.



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**Fig. 5 Artist's Version of Baseline Configuration DAWT with 18 Ft (5.5 m) Rotor Diameter
(Rated at 15 kW Output in 16 mph Wind) Installed at the DOE Rocky Flats Test
Facility**